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932 34

Ultraviolet imaging of hydrogen flames

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ABSTRACT

We have assembled an ultraviolet-sensitive intensified camera for observing hydrogen combustion by imaging the OH, $A^2\Sigma^+ - X^2\Pi$ bandhead emissions near 309 nm. The camera consists of a quartz and CaF achromat lense-coupled to an ultraviolet image intensifier which is in turn fiber-coupled to a focus projection scan (FPS) vidicon. The emission band is selected with interference filters which serve to discriminate against background. The camera provides optical gain of 100 to 1000 and is capable of being shuttered at nanosecond speeds and of being framed at over 600 frames per second. We present data from observations of test flames in air at standard RS-170 video rates with varying background conditions. Enhanced images using background subtraction are presented. Finally, we discuss the use of polarization effects to further discrimination against sky background. This work began as a feasibility study to investigate ultraviolet technology to detect hydrogen fires for the NASA space program.

1. INTRODUCTION

Hydrogen burns with very little emission in the visible making observation or detection difficult. Some previous work on this problem has been based upon using the infrared (IR) emission bands shown in the H_2 spectrum (Fig. 1) provided to us by NASA[1]. Hydrogen combustion in oxygen produces an OH emission band with a 10-nm full width at half maximum (FWHM) 309-nm bandhead from the $A^2\Sigma^+ - X^2\Pi$ transitions[2,3]. Our measurements of hydrogen (Fig. 2) burning in air at 7000 ft elevation show peak emission near 310 nm. At sea level the atmospheric content is higher for IR than for UV. We believe that IR-based detectors would have higher backgrounds to compete with the H_2 flame signal, resulting in poorer

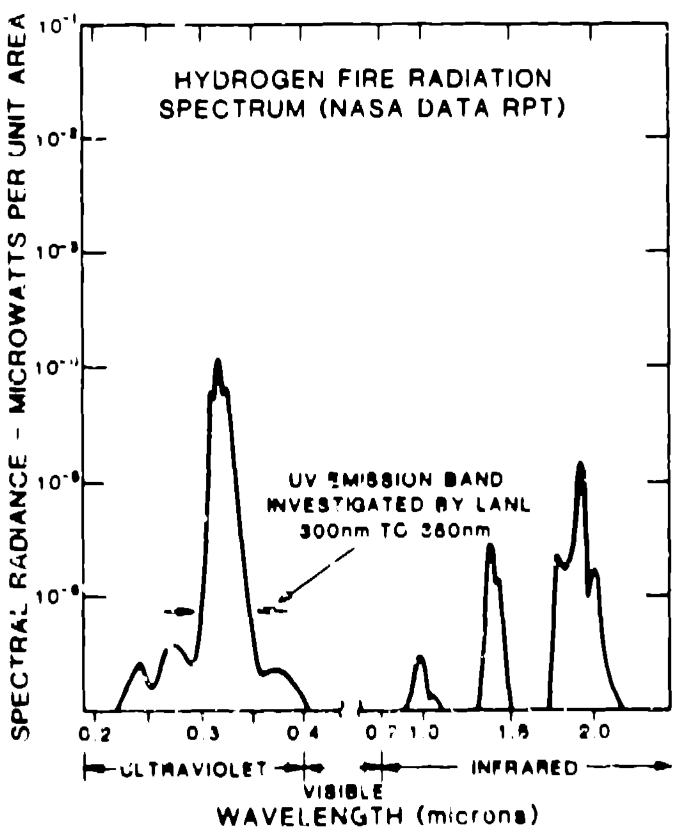

Fig. 1 Hydrogen fire radiation spectrum, replotted from data supplied by NASA

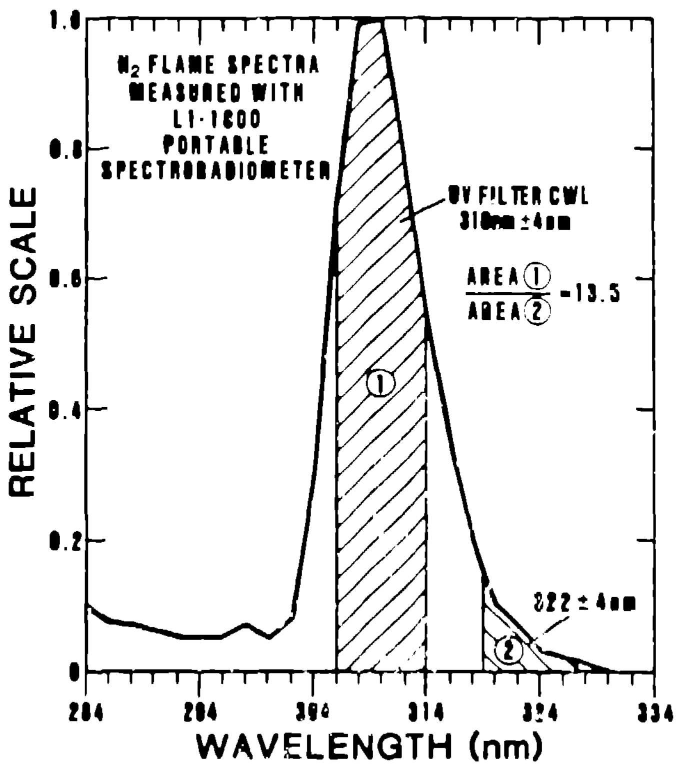

Fig. 2. Ultraviolet portion of hydrogen flame spectrum, in relative units normalized to peak (~310 nm ± 1 nm).

contrast images. In addition, the presence of combustion sources during ignition phases of a launch sequence would generate strong IR emission but virtually no UV emission.

Preliminary work involved using our UV camera and a spectroradiometer to measure the relative signal-to-background ratios of an H_2 flame burning in air under various background conditions including cloudy and sunlight conditions, dark and highly reflective backgrounds at Los Alamos, New Mexico (7000 ft elevation) and at Santa Barbara, California (sea level). A prototype system using UV optics, narrow band IR blocked UV notch filters, UV transmissive quartz faceplate image intensifier/vidicon TV readout was demonstrated at NASA's Cape Kennedy, Florida facilities with reasonable success.

Subsequent improvements, included (1) the use of background subtraction techniques by real time on-line processing of video frames using different optical filters with and without the H_2 flame as well as doing the subtraction later in our image processing laboratory using stored data and software algorithms; and (2) the use of polarization optics to attenuate background glare and reflections at a greater rate than the non-polarized H_2 flame signal.

2. SYSTEM DESIGN AND GOALS

The imaging requirements for the project were that a sufficient field-of-view (FOV) be provided to see an ~ 200 ft-diameter scene with enough resolution to detect a flame of 6-in height and 1-in width at distances from 50 ft to 1000 ft. The system would have to operate in both daylight conditions with high ambient lighting including possible reflections from sunlight and in night conditions with surveillance lighting (~ 200-ft candle illuminance) from Xenon lamps.

A brief description of our original UV system is given here, followed by analysis of its capabilities towards meeting the above conditions.

A simplified block diagram of our TV camera is shown in Fig. 3. The heart of the system is the UV sensitive components which are (1) narrow band UV notch filters with IR blocking, (2) UV transmissive Quartz/CaF/MgF lens, and (3) image intensifier with UV transmissive quartz faceplate and S-20 photocathode with high-quantum efficiency in the UV. The gain provided by the intensifier (~10^2 to 10^3) is required to amplify weak UV

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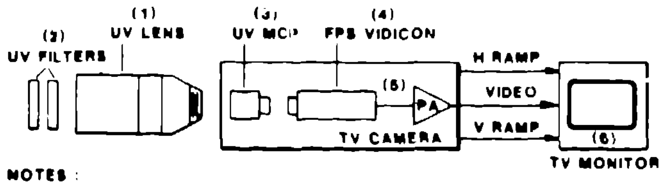


NOTES:

(1) UV LENS, ZEISS UV-SONNAR 7 ELEMENT CaF/MgF f4.3 105mm FOCAL LENGTH

(2) UV FILTERS, NOTCH: OMEGA OPTICAL INC 308nm ± 6nm AND 310nm ± 6nm

(3) UV MCP, ITT F-4111 18mm S-20 PHOTOCATHODE/QUARTZ INPUT AND P-20 PHOSPHOR/FIBER OPTIC OUTPUT

(4) TV READOUT, GE Z7803S SILICON TARGET FPS VIDICON/FIBER OPTIC INPUT

(5) TV CAMERA, XEDAR XS-503, RS-170 VIDEO FORMAT

(6) TV MONITOR, HEWLETT PACKARD 1311A XY DISPLAY

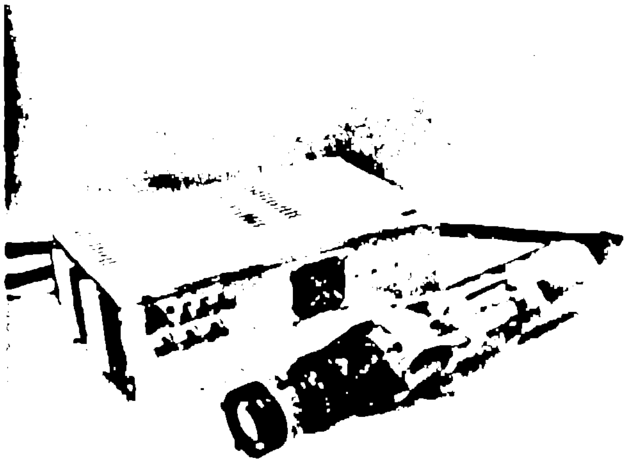


Fig. 3. The ultraviolet TV camera, with key components noted. The spectral transmittance of (1) is basically flat at 65% from 300 to 1000 nm; the "308 nm" filter has CWL of 308.5 nm, HBW of 12 nm, peak transmission of 20% and the "310 nm" filter has CWL of 309.5 nm, HBW of 9 nm, peak transmission of 19%; the intensifier photocathode (3) had ~ 9% QE and 22 mA/W at 310 nm; item (4) also used Sb_2S_3 target vidicon.

signals of interest which are strongly attenuated (to about 3 to 4% of original strength) in the process of filtering against other parts of the spectrum present in anticipated scenes. The image intensifier is fiber optically coupled to a high resolution Focus Projection and Scan (FPS) electrostatic deflected vidicon (4) that is used for TV readout. The TV camera (5) is a special design, fast-scanned radiometric unit used in our groups underground nuclear test diagnostic program. (Other vidicon/camera combinations are also suitable. Our familiarity with (4) and (5) as well as their availability prompted their use initially). The specifications of these components are summarized in the notes and caption for Fig. 3.

3. RESOLUTION REQUIREMENTS

The 18-mm diameter of the image intensifier photocathode limits the camera's FOV and its inherent limiting resolution (5 to 10% CTF) of approximately 20 ℓp/mm or 0.025 mm/pixel establishes the camera resolution along either axis. The FPS vidicon has about twice the resolution[4], achieving approximately 25 to 35μm point spread function (effective FWHM of the scan beam diameter) with 5 to 10% CTF at greater than 40 ℓp/mm. For the TV camera, in the vertical direction (axis) the quantity of raster lines (525 lines for the RS-170 format initially selected for ease in using conventional TV display and recording media) determines the resolution and in the horizontal direction (axis) the resolution is determined by both scan beam velocity (sweep speed) and video amplifier bandwidth.

At a distance of 200 ft our system resolution was estimated using 105 mm focal length and 18-mm diameter target. The system demagnification factor is 580:1 giving the camera a FOV of 34.3 ft diameter at the object plane with the 6-in flame height scaling to 0.0103 inches (0.262 mm) at the intensifier photocathode. The corresponding 1-in flame width is reduced to 0.00172 inches (0.0437 mm) at the photocathode. The 0.025 mm intensifier resolution is adequate in the vertical direction but marginal in the horizontal direction.

The TV vertical resolution of 525 lines/18mm (29 lines/mm) provides 7.46 lines/flame height which is sufficient to preserve the intensifier image. In the horizontal direction, combining the intensifier pixel size and the flame-width size in quadrature gives a first approximation flame width of ≈0.05 mm. Assuming no substantial further degradation by the FPS vidicon, the flame width represents an effective spatial frequency of approximately 180 cycles/line length. This is estimated by assuming the maximum times that the flame width (50μm) can be replicated periodically across the vidicon target diameter (18mm) with dead space (no image or unimaged area) between successive flame widths equal to the flame width itself. For the 52.4 μs line duration of RS-170 video, this spatial frequency is transformed to ≈3.44 MHz which is well within the bandwidth capabilities of the Xedar XS503 camera video chain (-3dB point adjustable downward from 25 MHz).

4. SENSITIVITY AND SIGNAL-TO-BACKGROUND MEASUREMENTS

4.1 Spectral and Radiometric Measurements

The flame that we studied was generated by flowing pure hydrogen through a 0.32-cm nozzle at a rate of 0.12 l/sec. The laminar flowing gas was ignited and burned steadily. The atmospheric pressure in Los Alamos is typically 580 torr. The slightly luminous flame was ~ 7 in (15- to 20-cm) high and 1.5 in (2- to 3-cm) wide and therefore had a 8-in^2 (50-cm^2) longitudinal cross section. A calibrated portable spectroradiometer (Li-Cor LI-1800) with 5-nm resolution equipped with a cosine integrating hemisphere and a radiometer with calibrated radiometric and interference filters were used to make spectral and radiometric measurements.

Figure 2 shows the H_2 flame spectrum in the spectral region of interest. The dominant emission feature is peaked at 309 nm with a FWHM of 10 nm and is probably due to emission from the unresolved $A^2\Sigma+ - X^2\Pi$ band of OH, an intermediate combustion product.

At 1 meter from the flame, we measured a flux of 2.5 nw/cm^2 in the OH band, implying a peak spectral radiance of about 5.6 X 10^{-8} watts/cm^2/nm/ster. Measurements at 309 nm were made of the spectral irradiance from the sun and the spectral radiance of the blue sky at a right angle to the direction of the sun. The radiance and irradiance measurements were made on "typical" clear, sunny days with the sun at about 45° elevation in Los Alamos and in Santa Barbara, Ca. The measurements are summarized in Table 1 along with our measured values of the solar constant which are given to provide an idea of the accuracy of the radiance and irradiance measurements. The radiance and irradiance measurements are consistent with previously published values (e.g. Ref. 3).

From the table we can see the solar irradiance and the blue sky radiance over 2π at 309 nm are comparable and larger than the flame irradiance. As will be seen in the following section, the measured video signals from reflective background sources are only comparable to the flame signal but not as large as Table 1 would predict. The low background is due to the low reflectivity of most objects at 309 nm. Table 1 also predicts that the flame signal should be a factor of 9 lower than the blue sky signal when the flame is imaged with a narrow band filter against the blue sky in Los Alamos. The video data in the next section show reasonable agreement with the value of 9.

TABLE 1
Background Sources

Location	Solar Const. (W/cm^2)	Solar Irradiance @309 nm (W/cm^2/nm)	Blue Sky Radiance @309 nm (W/cm^2/nm/ster)
Santa Barbara	0.10	4.0 X 10^{-6}	7.9 X 10^{-7}
Los Alamos	0.14	9.9 X 10^{-6}	5.2 X 10^{-7}
Ratio (SB/LA)	0.74	0.40	1.5

Although the largest contribution is shown to be from the sun rather than from the Blue Sky, the estimated overall reduction in UV at sea level is probably the sum of sun and Blue Sky at 309 nm (4.8 X 10^{-6} W/cm^2/nm/ster) compared with the similar sum (10.4 X 10^{-6} W/cm^2/nm/ster), for Los Alamos, or 2.2X.

4.2. Video measurements

Initial measurements at Los Alamos were done using available UV filters, most of which were broadband (> 50 nm) and not very well blocked outside their transmission band. Our best high-quality filter nearest the H_2 310 nm band was centered at 338.6 nm with base width of 12 to 14 nm. Referring to Fig. 2, the lower end of its transmission band only slightly overlaps the extreme high wavelengths "wing" of the H_2 band. Poor signal-to-noise ratios were obtained with video amplitudes of 50 mV and backgrounds of 2V. The system was subsequently operated at Cape Kennedy with similar results.

Special narrowband filters centered at 308 and 310 nm were obtained and used with a broadband (BB) filter in various combination, all of which provided improvements in the H_2 signal but with various trade-offs in signal-to-background (S/BG) and signal-to-noise (S/N) as indicated in Table 2. The BB filter was an Action Research Corp 320-N with center wavelength (CWL) of 320 nm, half bandwidth (HBW) of 22 nm, peak transmission of 14%.

The data were taken viewing the 7-in H_2 flame in daylight at several gain and high-voltage settings for the intensifier. All data presented were taken using the F4.3 105 mm UV-Nonnar lens, although we also experimented with a single element Plano Convex LiF F1 50

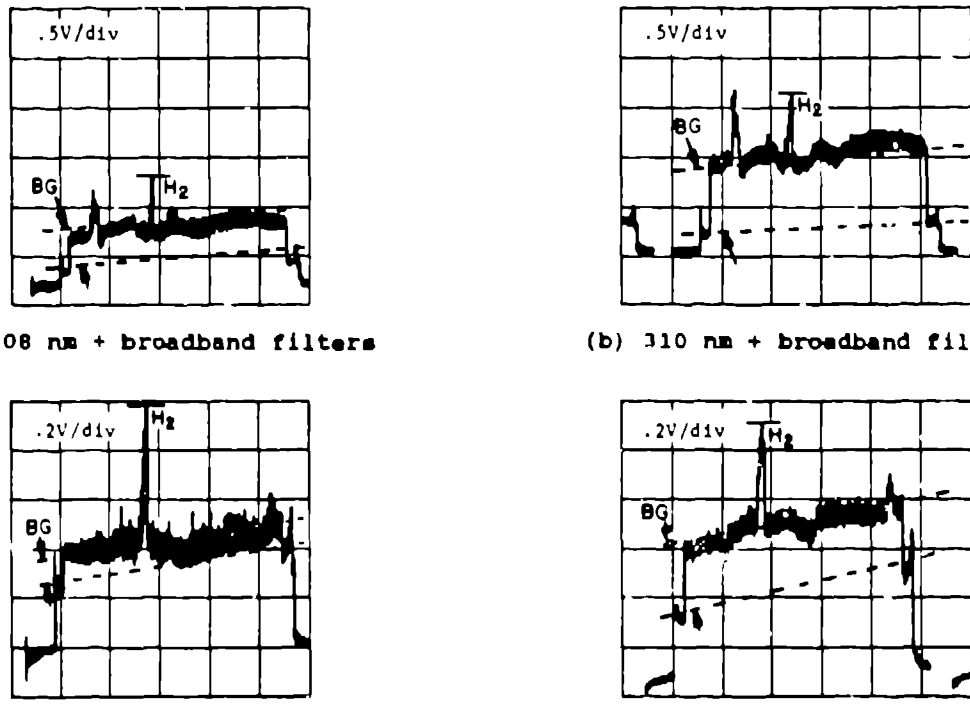
932 34

mm lens to see effects on flame-to-background ratios from the diffuse (unfocused) offband light provided by the single element.

TABLE 2.

Filter	MCP gain	HV	Signal	Background	S/BG	Noise	S/N
308+BB	Max	5.6KV	0.5V	0.5V	1/1	200MV	2.5/1
310+BB	Max	5.6KV	0.7V	0.7V	1/1	200MV	3.5/1
308+310	Max	6.0KV	0.6V	0.10V	6.0/1	100MV	6.0/1
310	< Max	6.0KV	0.45V	0.30V	1.5/1	50MV	9.0/1
310+BB	< Max	6.0KV	0.18V	0.1V	1.8/1	50MV	3.6/1
308+310	< Max	6.0KV	0.15V	0.05V	3/1	50MV	3/1

Oscilloscope traces which identify the H_2 signal, average background, and video amplifier noise components are shown in Fig. 4. By comparing traces a through d, the best



(a) 308 nm + broadband filters

(b) 310 nm + broadband filters

(c) 308 nm + 310 nm filters

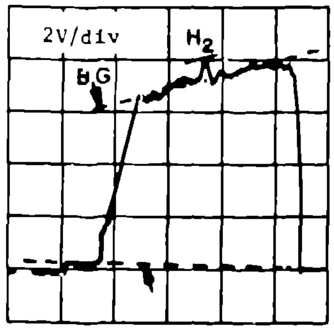
(d) 310 nm filter alone

Fig. 4. Hydrogen flame signal vs background for various filter and intensifier gain configurations. For a and b the intensifier gain was maximum and applied voltage was 5.6KV; for c the gain was maximum and voltage was 6.0 KV; for d both gain and voltage were reduced because of increased transmission.

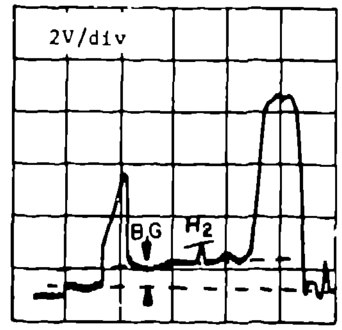
combination for highest S/BG is the 308 and 310 nm set. However, the S/N is poorer than with the 310 nm filter alone. conversely, for the 310 nm filter alone, the S/BG is poorer. We re-emphasize that these signal amplitudes can be improved significantly, and that potentially the best situation is to use two narrowband filters and boost signal levels above video noise by using faster lens (F1) or by increasing the sensitivity of the intensifier or vidicon.

The spectrometer data in Table 1 show a combined sun and blue sky background approximately 2X higher at Los Alamos (7000 ft) then at Santa Barbara (sea level). The video background levels obtained at 7000 ft compared with those at sea level confirm the spectrometer data. Of course the spectrometer data represents an average integrated flux since there is no imaging involved whereas the background levels detected by the TV camera do show variations within the scene that cannot be accurately compared for the two locations. However, as seen from Fig. 5, the nominal UV background at sea level is 2 to 3 times lower than at 7000 ft with the result that at sea level the 310 nm hydrogen spectrum (which is the same intensity at both locations) represents a stronger signal above background. In Fig. 5, oscilloscope traces show the hydrogen versus background signals for both locations; a, b, and c are for Los Alamos, and d is for Santa Barbara. The background at Los Alamos on a sunny day varied from 3 to 5 volts while at Santa Barbara, the level was 1 to 2 volts. For both locations the flame signal was approximately 700 mV.

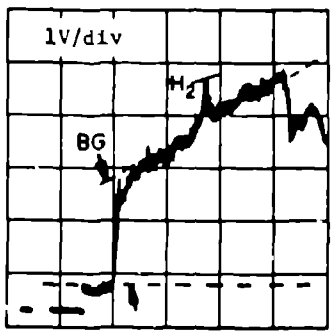
932 34



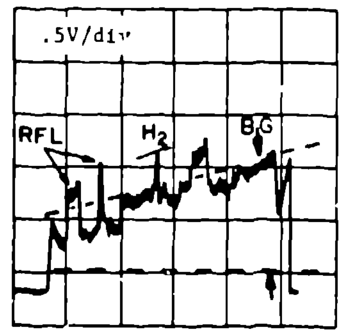
(a) Flame vs blue sky BG



(b) Flame vs black BG



(c) Flame vs nominal BG (7000 ft)



(d) Flame vs nominal BG (sea level)

Fig. 5. Hydrogen flame signal vs various backgrounds. In a the flame signal is against the blue sky; in b against the blue sky but with black surface behind the flame; in c against nominal background (all at 7000 ft). In d, the flame signal is against nominal background at sea level.

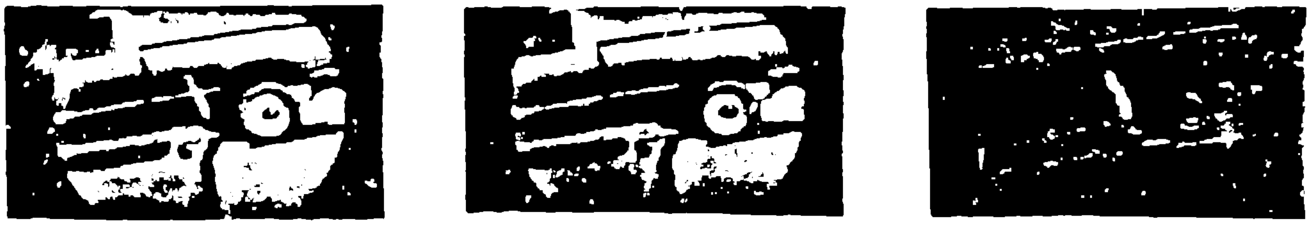
5. BACKGROUND SUBTRACTION

Enhancement of the H_2 flame was achieved by subtracting a background frame from one having the flame in it. This can be done in real time with video synchronized filter wheels. Filters centered on the H_2 emission line and just off the emission line with equal spectral width and transmissivity are needed. Referring to earlier Fig. 2, one can see the potential effect of such selective filtering.

The 322 ± 4 nm filter would transmit the same background as the 310 nm ± 4 nm, but would transmit 13.5X weaker H_2 signal, effectively representing a background frame. We briefly explored the technique but found that due to slightly different transmissions of the "on band" and "off band" filters, either too little or too much background was being subtracted. Consequently, rather than building up a filter wheel system, we recorded successive images for subtraction with and without an H_2 flame present. These were processed to simulate the resultant image one could obtain with a matched filter system. The data presented here were not processed in real time. The H_2 and background images were digitized in real time and stored on floppy disc for subtraction in our image processing laboratory later. We also used on line real time image subtraction based upon a Quantax ________________ digitizer/processor. However, the lack of a real time filter wheel system operating at video rates made analysis of those results different to interpret.

We used a light blue pickup truck in sunlight for background in Figs. 6a and b (left and center). Bright reflections from shinny surfaces were also in the scene. The pictures in Fig. 6a were taken with an Sb_2S_3 target FPS tube in the camera. Pictures were again taken (Fig. 6b) with a silicon target FPS tube in the camera and resulted in an improved H_2 signal of 1.5 volts amplitude vs 0.7 volts with the Sb_2S_3 tube. The silicon target also provided a linear response to light over its dynamic range. However, the sublinear transfer characteristic of the intensifier near saturation reduced the H_2 signal at higher backgrounds. In Figs. 6a and b (right), the results are the H2 image after background subtraction. The bright reflections (several times more intense than the flame signal) are virtually eliminated although the data appear to leave enough general background to show an outline of the pickup. This faint outline has the virtue of giving the location of the H_2 flame. Similar results can be acquired from appropriate selection of transmissivity for "on band" and "off band" filters described earlier.

932 34



(left) (center) (right)

(a) Blue pickup background (Sb2S3 vidicon)

(left) (center) (right)

(b) Blue pickup background (Silicon vidicon)

(left) (center) (right)

(c) Aluminum plate background (Silicon vidicon)

(left) (center) (right)

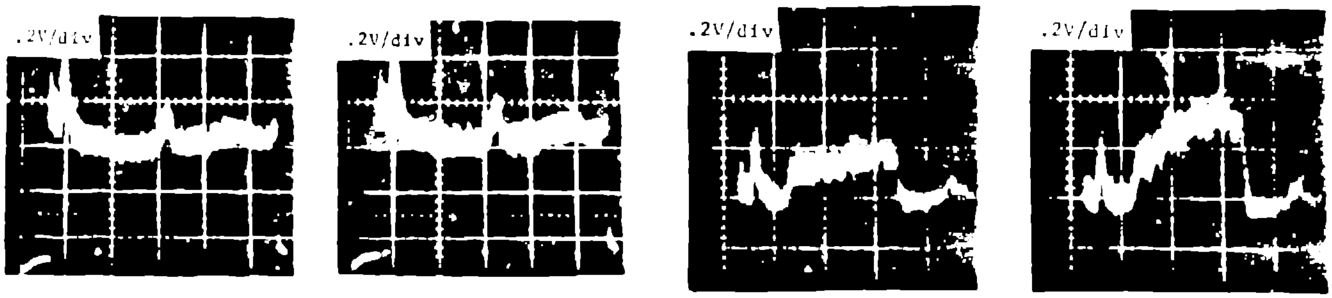
(d) Blue sky background (Silicon vidicon)

Fig. 6. Background subtraction sequences. For all sequences, the left photo is the background with the hydrogen flame signal; the center photo is the background only, and the right photo is the resultant flame signal after background subtraction. All data taken with daylight condition with flame at 50 ft distance and the 308 and 310 nm filter combination.

In Figs. 6c and d (left and center), two other backgrounds were used to provide more difficult tests in isolating the hydrogen flame. In Fig. 6c, a bright aluminum reflector was placed behind the flame. The most difficult test involved looking at the flame against the blue sky as shown in Fig. 6d.

The results from the background subtraction techniques are encouraging. However, if reflections are not exactly the same for the two images, they can produce signals that are difficult to distinguish from the flame signal as shown in Fig. 6d (right), where the backgrounds are different with the result that the subtraction was not very effective in isolating the flame signal.

932 34



a) H_2/polarizer @ 0° b) H_2/polarizer @ 90° c) BG/polarizer @ 0° d) BG/polarizer @ 90°

Fig. 7. Attenuation effects on hydrogen flame signal (a and b) and background glare from reflective aluminum plate (c and d) as functions of polarizer orientation.

6. POLARIZATION OPTICS FOR REFLECTION AND GLARE REDUCTION

We explored the possibility that polarized light from background sources could be substantial. The atmosphere is known to produce the "blue" of the sky by scattering this color preferentially from the white sunlight. This scattering phenomenon produces linearly polarized light. Also, we anticipated that reflecting surfaces could produce polarized background "glare". This effect is maximum at Brewster's angle and we would expect some superposition of light reflected from several angles so that the signal would be partially polarized. Thus, both the scattering and reflection mechanisms could play a role in producing background at 310 nm with a different polarization than the flame (assumed to be unpolarized).

We obtained an ultraviolet Glan-Thompson calcite prism polarizer with approximately 10^{-2}0% transmission at 310 nm and an extinction ratio of 1 X 10^{-4} in the "crossed" configuration. First, we tested the prism in series with the two notch filters on the hydrogen flame. As shown in Fig. 7a and b, only a slight difference in video levels was observed between the 0° and 90° orientations. We then used the polarizer in the sunlight with the aluminum plate as background. The plate angle was adjusted to obtain maximum glare. Figure 7c shows that with the polarizer aligned perpendicular to the plane of reflection (i.e., vertical), we see about a 50% reduction in the UV background compared with the horizontal alignment, Fig. 7d.

In conclusion, the use of a polarizer has the capability of reducing the UV background component at 310 nm by about 50% in some circumstances. This results in an improvement in the hydrogen signal-to background by a factor of 2X for some scenes. However, the flame signal itself already severally attenuated by the notch filters (~ 4% of original strength) is further attenuated, resulting in reduced signal-to-video noise ratio of approximately 1.5/1 as shown in Fig. 7a or b.

7. ACKNOWLEDGEMENTS

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